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DYNAMIC TIME RESPONSE OF TEFLON-COATED THERMOCOUPLES

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SUMMARY: Time constants were determined for teflon coated thermocouples. Percent error was determined for sinusoidal and linear dynamic time responses. Potential errors are simulated for various air and soil temperature scenarios. Soil temperature measurement errors should be less than 0.7°C. Thermocouple size and rate of cooling are important when determining the supercooling temperature of insects.

KEYWORDS: thermometry, dynamics, insects, thermocouple, teflon.

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DYNAMIC TIME RESPONSE OF TEFLON-COATED THERMOCOUPLES[1]

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ABSTRACT

Thermocouples are covered with teflon to electrically insulate them from each other when placed in soil. Thermal response may be delayed because good electrical insulators are generally also good thermal insulators. Time constants were determined for bare thermocouples and teflon-coated thermocouples. Percent error due to dynamic time response was determined for various time constants and simulated sinusoidal signal inputs. The dynamic response of a first-order instrument to a step-change, linear-change, and a sinusoidal signal are described mathematically. Potential errors were determined for various soil and air temperature, and time-cycle scenarios using numerical computer simulations. Maximum measurement error when using teflon-coated thermocouples in soil should be less than 0.7 degrees Celcius, and generally will not be a concern when measuring air temperature. Concern must be given to using the proper thermocouple size and rate of temperature change when using thermocouples to determine the supercooling point of insects. Keywords: thermocouple, thermometry, teflon, dynamics, insects

INTRODUCTION

Accurate measurement of temperature is an important aspect of biological and environmental science. Temperature can be measured by numerous types of measurement devices. Thermocouples are convenient for measuring temperature because they generate an electrical signal that can be automatically recorded with a data recorder. Thermocouples are small, rugged, highly reliable, responsive, inexpensive, and easy to work with. Copper-constantan thermocouples (Type-T) are the most common type used for measurement of air temperature in micrometeorology (Rosenberg et al, 1983).

Thermocouples used for soil temperature measurements should be encased in materials that are good electrical insulators (e.g., teflon, epoxy resins, etc.) to avoid the development of "ground loops" that introduce spurious electrical signals into measurement circuits (Rosenberg et al, 1983). However, materials that are good electrical insulators are generally good thermal insulators, also. Consequently, the combination of the insulating property and the increased thermal mass can reduce the responsiveness of thermocouples to temperature changes.

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Thermocouples are also used for measuring temperatures important for biological functions. An example is the determination of the supercooling point of insects. An accurate determination of the supercooling point is required for understanding environmental effects on insect mortality. The objectives of this study were to:

1. determine time constants of thermocouples constructed in various ways typical of biological and environmental measurements,
2. determine magnitudes of errors under varying temperature conditions that occur as a result of varying time constants of thermocouples of differing construction, and
3. analyze implications of measurement errors that might occur relative to selected biological and environmental situations.

METHODS AND MATERIALS

Thermocouples (TC) were constructed from 24 AWG and 30 AWG copper-constantan (Type-T) wire by stripping 10 mm of insulation from the wire pair, twisting the wire together to form a junction, and soft-soldering the junction with rosin-core flux electronic solder. The excess portion of the twisted pair was then trimmed from the thermocouple junction.

The teflon-coated TC were made by epoxy-gluing the 24 AWG TC into either 6.4 mm diameter teflon balls or into 9.5 mm diameter by 9.5 mm length teflon cylinders. An additional configuration was made by coating a 24 AWG TC with a 6 to 7 mm ball of silicon rubber adhesive sealant.

Time response analysis was conducted on bare TC junction of both wire sizes; 24 AWG TC coated with the teflon ball, teflon cylinder, and the silicon ball; and a gas-filled metal tube (GFMT) connected to a bourdon tube and strip chart recorder (Belfort[3] Model 5-1125, Belfort Instrument Co., Baltimore MD). The GFMT probe is 2.5 cm in diameter and 35 cm long and has been used to measure soil temperature. It has a relatively large thermal mass and slow dynamic response when compared to TC and will provide a comparison of old and new technology.

Time constant determination

Temperature measurement devices like thermometers and TC are treated as first-order dynamic instruments because they do not exhibit oscillary motion, mass transfer or damping (Henry, 1975). The dynamic response of a first-order instrument (FOI) is defined as the rate of change of the instrument response multiplied by a time constant for the instrument (Graham, 1975). This dynamic response is the difference between measured and actual values of the measured parameter. The time constant can be determined for thermocouples by measuring the dynamic response to a step

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3. Note: The mention of tradenames or commercial products does not constitute their endorsement or recommendation for use by the USDA Agricultural Research Service.

change of the measured parameter (Henry, 1975). The mathematical expression for the dynamic response to a step change of a FOI is:

$$\tau \frac{dy}{dt} + y = y_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1.$$

where, t = time constant, [t]
y = measured parameter, [some unspecified dimension (SUD)]
t = time dimension, [t]
y_s = actual constant value of step increase, [SUD]

The solution (Derrick and Grossman, 1976) to equation 1 is:

$$\frac{y}{y_s} = 1 - e^{-t/\tau} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.$$

If time t equals the time constant τ in eq. 2, y/y_s equals 0.632, so the time constant is the time it takes a FOI to respond to 63.2 % of a step change in the measured parameter. Time constants for the various temperature measuring devices in this experiment were determined by measuring their response to a step temperature change, for both air and water as the temperature conducting media. Time constants for water were determined by placing each device from ambient air (approx. 22 °C) into ice water. Time constants for air were determined by removing each device from a food freezer into ambient still air. The thermocouples were referenced to an electronic ice point using an Omega CJ thermocouple cold-junction compensator which has an accuracy of 0.5 °C. The temperature response was measured and recorded with a Cyborg ISAAC 2000 data acquisition system (DAS) connected to a portable computer. The accuracy of the DAS was 1 mv and the sampling rate was 50 hertz. Software for the DAS was used to determine the time for each instrument to respond to 63.2 % for the step change in temperature. The time constant tests were replicated three times and averaged.

Sinusoidal signal dynamic response

Since ambient soil and air temperatures fluctuate in a sinusoidal fashion, the dynamic response of a FOI to a steady state sinusoidal temperature change was analyzed for various time constants and sinusoidal period time lengths. The dynamic response of a FOI to a steady state sinusoidal change is defined mathematically as:

$$\tau \frac{dy}{dt} + y = A \sin(\omega t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.$$

where, A = magnitude of the actual signal, [SUD]
ω = cycle frequency, [1/t]

The solution to equation 3 is:

$$y = \frac{1}{(1 + (\omega\tau)^2)^{0.5}} \sin(\omega t - \phi) \quad \text{. 4.}$$

$$\phi = \tan^{-1} (\omega t) \quad \text{. . . . . 5.}$$

where, ϕ = steady-state lag angle, [nondimensional]

The lag angle is the angular displacement that the measured response lags behind the actual signal. Analysis of a sinusoidal response can determine the time lag of the measured signal to the actual signal, and the measurement error due to the dynamic response at any phase of the signal. Of particular significance is the reduction in peak values of measured to actual signal, and maximum error which occurs near maximum rate of signal change.

Linear signal change dynamic response

During periods of maximum soil or air temperature change, measured temperature response approaches a steady-state linear dynamic response. Steady-state dynamic response of a FOI to a linear signal change is defined mathematically as:

$$\tau \frac{dy}{dt} + y = kt \quad \text{. . . . . .6.}$$

where, k = a constant rate of change of the signal, [SUD/t]

The solution of equation 6 is:

$$y = kt - k\tau + k\tau e^{-t/\tau} \quad \text{. . . . . 7.}$$

For steady-state conditions where the value of time becomes much greater than the time constant, the difference between actual and measured signal values, or measurement error, equals the rate of signal change, k, multiplied by the time constant, τ, or:

$$y_{error} = k\tau \quad \text{. . . . . 8.}$$

where, y_{error} = steady-state, linear signal, measurement error, [SUD]

RESULTS AND DISCUSSION

Time constant determination

The time constants for both air and water are shown in Table. 1. The smaller TC (TC-30) has a smaller thermal mass and therefore a shorter time constant and a faster dynamic response. A thermocouple glued into a piece of teflon has a longer time constant and consequently a slower dynamic response because the teflon adds more mass and thermal insulation. This silicon-coated TC has time constants similar to that of the 6.4 mm teflon ball TC.

Sinusoidal temperature measurement error

The dynamic time response of a sinusoidal signal can be determined mathematically or computer-simulated numerically. The response was simulated numerically for cycle periods ranging from 5 seconds to 24 hours, and for various time constants. Percent peak signal differences and maximum signal differences were determined, and are illustrated in figure 1 for a 30 minute cycle with time constants varying from 1 to 900 seconds. Percent peak signal difference is the drop in peak signal amplitude due to the time response compared to the amplitude of the actual signal. Maximum percent signal difference is the maximum difference between measured and actual signal as a percent of actual signal amplitude, and usually occurs near signal inflection points where signals have their greatest rate of change. Percent peak signal differences are shown in table 2. The percent maximum signal differences are shown in table 3. The greater the time constant and/or the shorter the signal cycle time, the greater the peak signal error and the maximum signal error.

Soil temperature measurement error

Soil temperature measurement errors are dependent on the amount of soil contact with temperature measuring device. Results will be shown as a temperature range, with the lower value being that for water and the upper value being that for air. Since soil is a combination of earth, air and water, the heat conducting property of soil will depend on the amount of air and water in the soil. A wet soil may conduct heat similar to that of water, and a loosely-packed, dry surface soil may conduct heat similar to that of air.

Analysis and discussion will be made for TC-ball and TC-cyl. Teflon-coated TC are commonly used for soil temperature measurement to minimize electrical interference between TC that are placed closely together in the soil. Sinusoidal cycle periods of 1, 4 and 24 hours will be considered with maximum to minimum temperature changes of 2, 5 and 30 degrees Celsius, respectively. Similar cycles of soil temperatures were measured in the field at a soil depth of 50 mm, as shown in figure 2. The measurement error of these TC for these time and temperature cycles are shown in table 4. Using linear change analysis (Eq.8) and a 5 ℃ per hour temperature change, TC-ball has a potential measurement error of 0.01 to 0.12 ℃ and TC-cyl. has an potential error of 0.03 to 0.25 ℃.

The GFMT with an assumed soil conducting time constant of approximately 900 seconds would have a PTE of 0.92, 0.18 and 0.04 °C, and a MTE of 1.7, 0.92 and 1.2 °C, for the 1, 4 and 24 hour cycles, respectively. Linear response analysis predicts a 1.25 °C temperature measurement error for the GFMT at a 5 °C/hr rate of temperature change.

Air temperature measurement error

Errors in measuring air temperature are generally not significant when using thermocouples. However, when using teflon-coated thermocouples under highly dynamic temperature changes, significant errors possibly can occur. For the 24 hour, 30 °C sine-wave temperature cycle, bare TC exhibit negligible PTE and less than 0.05 °C (0.36%) MTE. A 30 °C (54 °F) maximum to minimum daily temperature difference is not uncommon in the central U.S. From a linear response analysis, with a 20 °C per hour temperature change (a possible, although not common rate of temperature change), temperature measurement error using a bare TC is less than 0.3 °C.

If teflon-coated TC are used to measure air temperature, they have much greater measurement error. For a 24-hour, 30 °C cycle, PTE is 0.005 °C and MTE is 0.28 °C with the TC-cyl. Linear response analysis predicts a 1.2 °C measurement error for a 20 °C per hour rate of temperature change. Therefore, care must be taken when using teflon-coated TC for measuring instantaneous air temperature. The teflon coating sufficiently increases the time constant of the TC and can cause significant errors when measuring instantaneous air temperature.

Aphid supercooling point measurement error

Russian wheat aphids (RWA) have body fluid containing a natural antifreeze (similar to glycerol or glycol) to help them survive through the winter season. The freezing point or "supercooling point" of RWA is considered the RWA's lowest cold tolerance level and is used in overwintering research. The supercooling point is determined by placing them on a fine guage wire TC coated with a thin film of petroleum jelly, and lowering the temperature until the body fluids freeze. When the body fluids freeze, latent heat of fusion is released which momentarily raises the aphid temperature which is detected as a small spike in the measured temperature signal. The RWA typically freeze at approximately -27 °C. If the rate of temperature change is too rapid and/or the TC time-response is too great, then time-response measurement error may be significant with resultant inaccurate conclusions of the supercooling temperature of RWA mortality.

Since the RWA is in contact with the TC, the TC should conduct heat to/from the RWA similar to that of water, and consequently, have time constants similar to water. If the rate of change of temperature is 3 °C per second, the larger TC-24 has a 2.4 °C measurement error. If the rate of temperature change is 0.33 °C per second, TC-24 has a 0.27 °C measurement error. For this experimental application, it is better to use the smaller size TC-30 at a relatively slow rate of temperature change because temperature measurement error is only 0.3 °C and 0.03 °C for a 3 °C/sec and 0.33 °C/sec rate of change, respectively.

CONCLUSIONS

Time constants of teflon-coated TC were 4 times greater in air and 30 times greater in water than that of bare TC due to the additional thermal mass and resistance of the teflon cover. Maximum signal error can be significant (>3%) for bare TC in air and water for cycle periods shorter that 4 hours and 1 minute, respectively. Maximum signal error for teflon-coated TC in air and water can be significant for cycle periods shorter than 1 day and 30 minutes, respectively. Soil temperature measurement errors using teflon-coated TC should generally be less than 0.7 °C. Errors in measuring air temperature with teflon-coated TC may be as great as 1.2 °C during periods of rapid temperature change. However, teflon-coated TC should generally not be a concern when measuring instantaneous air temperature. The use of TC for biological experiments requires some analysis of time response characteristics because errors may be significant for large size thermocouples (large time constants) and high rates of temperature change.

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Table 1. Time constants for various temperature measuring devices for air and water.

Temperature Measuring Device	Time Constant (sec) Air	S.D.	Water	S.D.
30-AWG wire TC, bare, (TC-30)	10	0.7	0.1	0.006
24-AWG wire TC, bare, (TC-24)	51	0.3	0.8	0.06
TC-24, with a 6.4 mm teflon ball, (TC-ball)	111	5.7	8	0.14
TC-24, with a 9.5 mm teflon cylinder (TC-cyl)	218	16.3	25	0.6
Gas-Filled Metal Tube (GFMT)	2100	---	150	---

Table 2. Percent peak signal difference of a sinusoidal time response.

Period	Time constant (seconds) 1	8	12	25	50	110	220	900
1 day	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.03	0.21
6 hrs	<0.01	<0.01	<0.01	0.01	0.02	0.10	0.20	3.26
4 hrs	<0.01	<0.01	<0.01	0.01	0.05	0.13	0.50	6.92
2 hrs	<0.01	<0.01	0.01	0.05	0.11	0.50	1.79	21.4
1 hr	<0.01	0.02	0.04	0.11	0.41	1.79	6.65	64.3
30 min.	<0.01	0.08	0.11	0.41	1.50	6.65	10.7	69.7
10 min.	0.01	0.37	0.78	3.26	11.4	34.5	60.2	89.4
3 min.	0.10	3.71	7.78	24.7	50.3	74.8	87.1	96.2
1 min.	0.57	23.3	37.7	64.3	83.2	91.3	95.7	98.9
15 sec.	7.78	71.4	80.5	90.5	95.2	97.8	98.9	99.7
5 sec.	37.8	80.1	93.4	96.8	98.4	99.3	99.7	99.1

Table 3. Maximum percent signal error of a sinusoidal time response.

Period	Time constant (seconds) 1	8	12	25	50	110	220	900
1 day	0.01	0.06	0.09	0.18	0.36	0.80	1.60	6.53
6 hrs	0.03	0.23	0.35	0.73	1.45	3.20	6.35	24.9
4 hrs	0.04	0.35	0.52	1.09	2.18	4.79	9.55	36.5
2 hrs	0.09	0.70	1.05	2.18	4.36	9.55	18.8	61.7
1 hr	0.17	1.40	2.09	4.36	8.69	18.8	35.8	84.4
30 min.	0.35	2.79	4.18	8.69	17.2	35.8	60.9	95.3
10 min.	1.05	8.35	12.5	25.3	46.4	75.5	91.7	99.4
3 min.	3.49	26.9	38.6	65.7	86.7	96.8	99.2	99.9
1 min.	10.4	64.2	78.2	93.4	98.2	99.6	99.9	100
15 sec.	38.6	95.8	98.1	99.5	99.9	99.9	100	100
5 sec.	78.3	99.5	99.8	99.9	100	100	100	100

Table 4. Peak temperature error (PTE) and maximum temperature error (MTE) for teflon-coated thermocouples under various soil temperature ranges and time cycles.

Cycle length	Temp. range	Peak temperature error TC-ball	TC-cyl.	Maximum temperature error TC-ball	TC-cyl.
1 hr.	2 °C	0.04 °C (1.8%)	0.13 °C (6.6%)	0.03–0.4 °C (1.4–19%)	0.09–0.7 °C (4–36%)
4 hr.	5 °C	0.003 °C (0.13%)	0.012 °C (0.5%)	0.01–0.12 °C (0.35–4.8%)	0.03–0.25 °C (1.0–9.6%)
24 hr.	30 °C	0.002 °C (0.01%)	0.14 °C (0.8%)	0.0–0.005 °C (0.0–0.03%)	0.04–0.3 °C (0.2–1.6%)

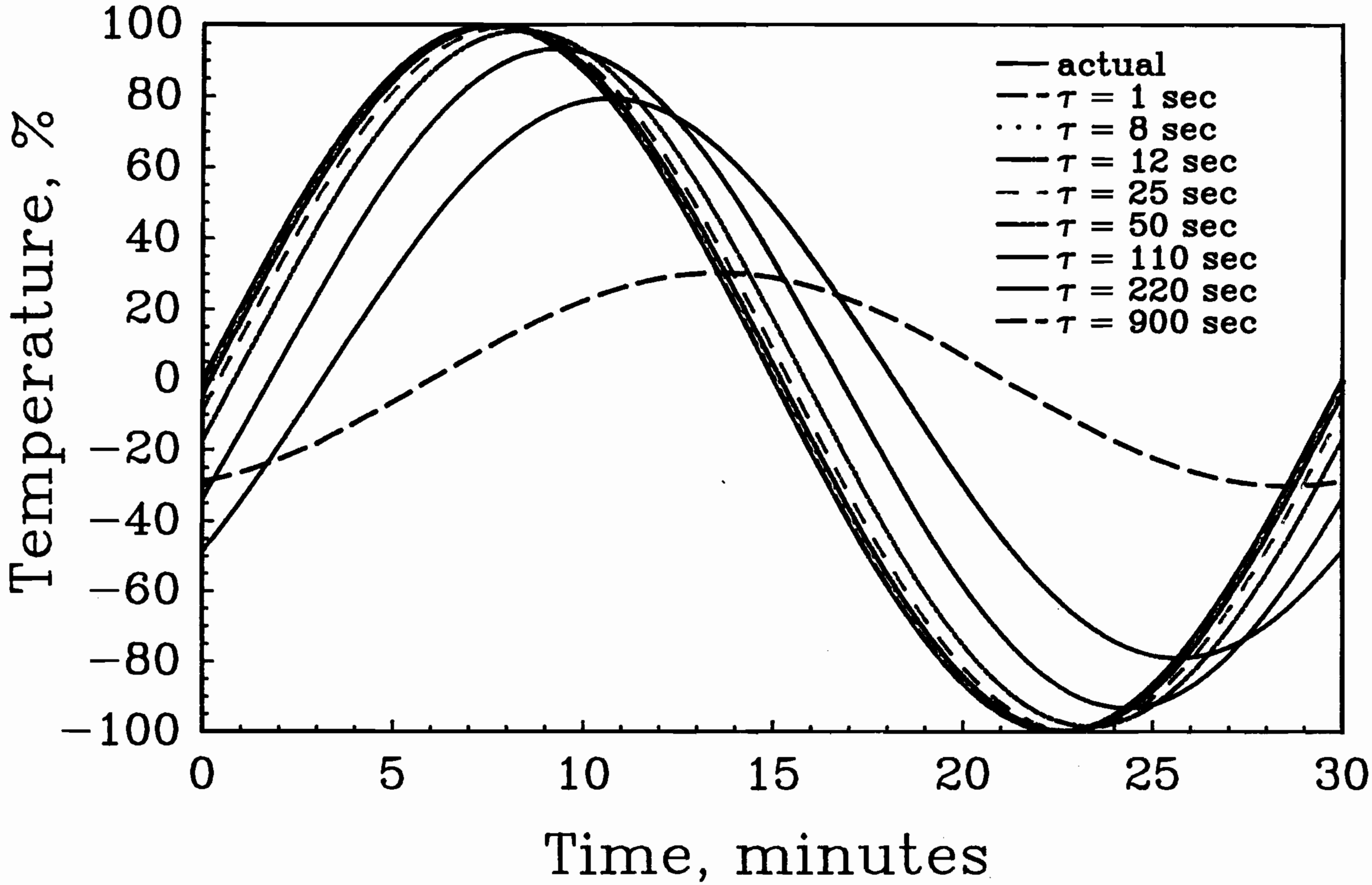

Figure 1. **Instrument dynamic response to a 30 minute sinusoidal signal for various time constants (τ).**

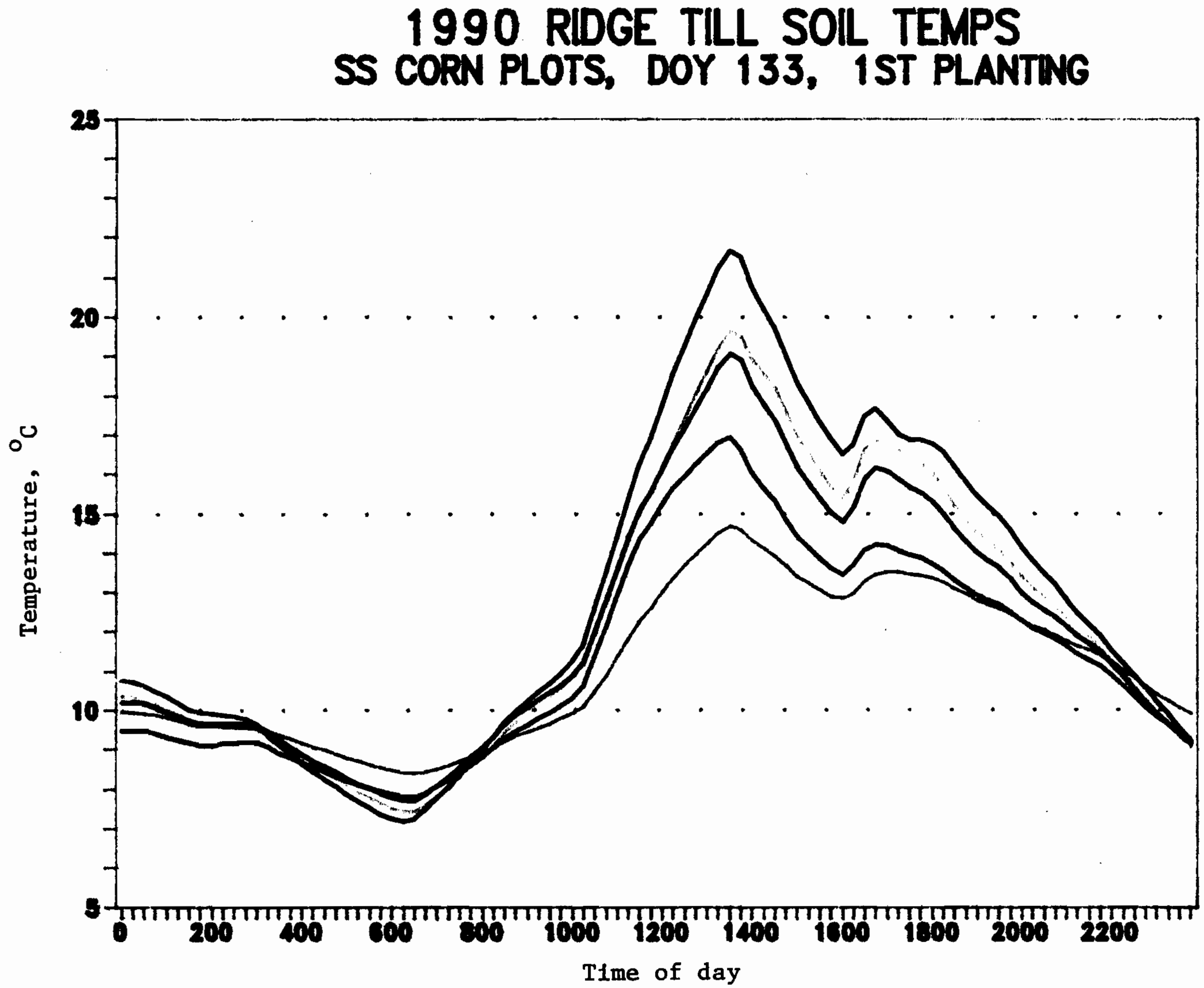

Figure 2. Typical soil temperature measurements at a 50 mm depth for 1 day, which also show approximate partial phases of 6 and 2 hours cycles. Julian Day 133 = May 13.